$B_{s(d)} \rightarrow \mu^+\mu^-$ with 7 fb$^{-1}$ of CDF Data

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Motivation

- $B_s \to \mu^+ \mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- This decay is not only suppressed by the GIM Mechanism but also by helicity
- SM predicts very low rate with little SM background ($\mathcal{B}R(B_s \to \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, Andrzej J. Buras et al, JHEP 1009 (2010) 106
- BSM models predict enhancement
- Ratio of $\mathcal{B}R(B_s \to \mu^+ \mu^-)$ and $\mathcal{B}R(B_d \to \mu^+ \mu^-)$ is important to discriminate amongst BSM models
- Clean experimental signature → τ’s would have stronger coupling but experimentally difficult
The Measurement

- Measure rate of $B_s \rightarrow \mu^+ \mu^-$ relative to $B^+ \rightarrow J/\Psi K^+$, $J/\Psi \rightarrow \mu^+ \mu^-$
- Apply same selection to find $B^+ \rightarrow J/\Psi K^+$
- Systematic uncertainties will cancel in ratio ⇒ e.g. dimuon trigger efficiency is the same for both modes

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) = \frac{N_{B_s}}{N_{B^+}} \frac{\epsilon_{B^+}}{\epsilon_{B_s}} \frac{\alpha_{B^+}}{\alpha_{B_s}} \frac{1}{\epsilon_{NN_{B_s}}} \frac{f_{\mu}}{f_s} \cdot \text{BR}(B^+ \rightarrow J/\Psi K^+ \rightarrow \mu^+ \mu^- K^+)$$

From Data, From MC, From PDG

- $N_{B^+} \sim 2 \times 10^4$, $\frac{\epsilon_{B^+}}{\epsilon_{B_s}} \sim 1$
- $\frac{\epsilon_{B^+}}{\epsilon_{B_s}} \sim 1$, $\frac{\alpha_{B^+}}{\alpha_{B_s}} \sim 0.5$, $\frac{1}{\epsilon_{NN_{B_s}}} \sim 1$
- $\frac{f_{\mu}}{f_s} \sim 3$, $\text{BR}(B^+ \rightarrow J/\Psi K^+ \rightarrow \mu^+ \mu^- K^+) \sim 5 \times 10^{-5}$
Analysis Flow Chart

- Estimate acceptances and efficiencies
- Identify variables that discriminate signal and background
- Make multivariate discriminant, for background rejection
  - Optimized with Pythia signal MC and data mass sideband
  - Validate in $B^+$ sample
- Estimate Background
  - Combinatoric background
  - Peaking background: $B \to \mu^+\mu^-$
- Unblind
Signal vs. Background

Signal Properties

- Final state fully reconstructed
- $B_s$ is long lived ($c\tau \approx 450 \mu m$)
- $B$ fragmentation is hard: few additional tracks

Background contributions & characteristics

- Sequential semi-leptonic decay: $b \rightarrow c\mu^- X \rightarrow \mu^+\mu^- X$
- Double semi-leptonic decay: $bb \rightarrow \mu^-\mu^+ X$
- Continuum $\mu^+\mu^-$
- $\mu^+$ fake and fake+fake
  - Partially reconstructed
  - Softer
  - Short lived
  - Has more tracks
- $B \rightarrow hh$: peaking in signal region
### Data Sample and Signal Selection

#### Central-Central (CMU) and Central-Forward (CMX) Di-muon Trigger

- **Central**: $p_T > 2.0$ GeV and $|\eta| < 0.6$ – **Forward**: $p_T > 2.2$ GeV and $0.6 < |\eta| < 1.0$

- $p_T$ cuts restrict us to well understood trigger regions

### Basic Quality Cuts

- Tracker tracks with hits in 3 silicon layers
- Likelihood and dE/dx based muon Id
- Vertex Quality
- Various Baseline Cuts
  - $p_T(\mu^+\mu^-) > 4.0$ GeV;
  - Loose Isolation and opening angle (pointing) cuts

Still background dominated after a reduction of events of 4 orders of magnitude
Neural Network

- New 14-variable NN to increase S/B
- Carefully chose input variables to avoid bias in $M_{\mu\mu}$

NN Input Variables

- $\lambda$ (proper decay length)
- Isolation
- Pointing angle
- $\lambda/\sigma_\lambda$
- lower $p_T(\mu)$
- Secondary vertex $\chi^2$
- Decay length ($L_{3D}$)
- Transverse Decay length significance ($L_{xy}/\sigma_{L_{xy}}$)
- 2D Pointing angle
- Smaller impact parameter
- Larger impact parameter
- Smaller impact parameter significance
- Larger impact parameter significance
- $B_{s(d)}$ impact parameter
Background Estimates

Combinatorial Background

- Use sideband to estimate combinatorial background in signal window
- Assign systematic errors on background estimates based on slope variation
- Highest 3 NN bins have additional systematic from uncertainty of background shape

Peaking Background

- $B \rightarrow hh$ processes where both hadrons (either kaons or pions) are misidentified as muons
- Estimate fake rate dataset rich in kaons and pions ($D^*_{-}$-tagged $D^0 \rightarrow K^+\pi^-$)
- Use MC to simulate kinematics of processes
Signal contains two opposite signed muons with positive lifetime ($\vec{p}_{B_s(d)}$ aligned with primary to secondary vertex vector)

Checked background estimates with 4 control samples
- Opposite sign muons with negative lifetime ($\vec{p}_{B_s(d)}$ anti-aligned with primary to secondary vertex vector)
- Same sign muons with positive lifetime
- Same sign muons with negative lifetime
- Fake muons with positive lifetime (Fake muons = muon that failed muon ID requirements)

Followed our procedure for background estimation in each control sample for all mass and NN bins

Compared estimate with observed events in blinded region

Checked background with 64 samples $\Rightarrow$ good agreement between predicted and observed
Results: Unblinded Mass Plots

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$B_s \rightarrow \mu^+ \mu^-$
Results: Limits and P-Values

Limits

• Set limits using CLs methodology
• No excess in $B_d$, limit:
  $\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) \leq 6.0 \times 10^{-9}$ at 95% C.L.
• Significant excess in $B_s$, limit:
  $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) \leq 4.0 \times 10^{-8}$ at 95% C.L.

P-Values

• Generate background only MC
• Compare observed LLR ($\frac{P(s+b|\text{data})}{P(b|\text{data})}$) value with LLR distribution of MC
• P-value for bkg only hypothesis: 0.27%
• P-value for SM+bkg hypothesis: 1.9%
• Estimate central value for $B_s$ case using $\chi^2$ fit
• Measured central value:
  $\mathcal{B}(B_s \to \mu^+ \mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$
• 90% bounds: $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+ \mu^-) < 3.9 \times 10^{-8}$
Summary

- First two sided limit from CDF using 7 fb$^{-1}$ of data
- Compatible with limits set by CMS and LHCb
- Plan to update the analysis with full CDF dataset ($\sim 10$ fb$^{-1}$)